Title: DARHT Axis II Cell Solenoid Magnet Shunt Resistance

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Abstract

DARHT Axis-II cell solenoid magnets have exhibited significant degradation since initial manufacture. A recent redesign of these magnets has provided an opportunity to revisit the dielectric performance to ensure high quality magnets are obtained. Magnet test specifications are shown to be consistent with those recommended in the literature and in use by practicing magnet engineers. A dielectric analysis of the coil reveals that the epoxy layer thickness and integrity are critical to meeting the required performance but are not adequately controlled in the present specification. Remedies to the coil fabrication process are provided.

1 Introduction

Cell solenoid magnets in the DARHT Axis-II accelerator have exhibited degradation since initial installation. A redesign has been completed to reduce the total stresses in the magnet during operations[1]. In order to further improve the operation and lifetime of the magnets, the fabrication processes associated with the magnet have been studied and several areas identified for modification.
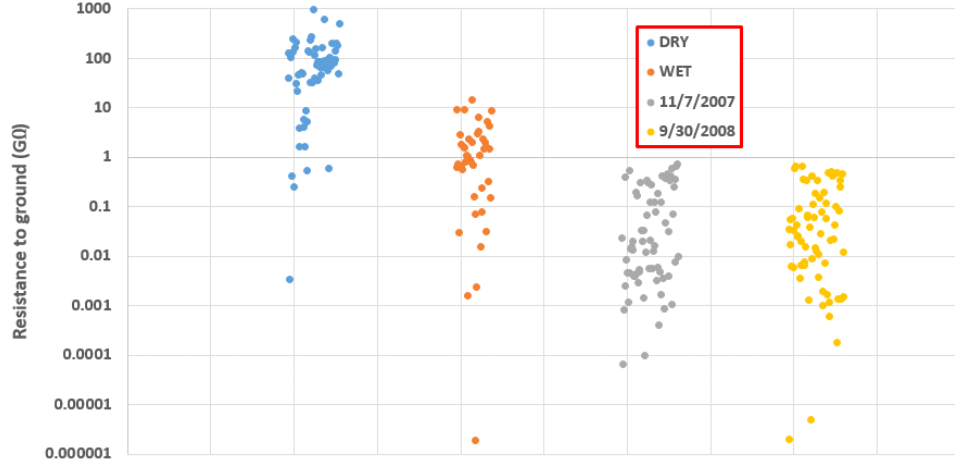
Figure 1: Measured resistance to ground at different time of the coil testing and operation. See text for details.

2 Design and historical performance of the Axis-II cell solenoids

The Axis-II cell solenoids are wound from 13 gauge square copper conductor. The conductor is coated with 0.004" Formvar insulation in the original design developed at LBNL. The solenoid is wound in 12 layers with a nominal 194 +/- 4 turns per layer. A thermally conductive epoxy[2] is "painted" on each layer of conductor before and after winding the layer. After winding, the magnet is coated with additional epoxy on the ID and OD for electrical insulation. The final magnet is a rigid cylinder. Note that all original solenoid magnets in the injector, BCUZ, and accelerator are fabricated using the same magnet wire and winding process. The completed solenoid magnets are assembled into a sleeve that allows cooling water to flow across the coil inner and outer surfaces.

After installation in the accelerator cells and periodically thereafter beginning in 2007, the magnets were hi-potted to measure the resistance to ground as well as the coil resistance. Two significant problems were identified:

1. The magnet resistance to ground was significantly lower than prior measurements made during fabrication.

2. The measured magnet resistance of a few magnets was lower typically corresponding to an integral number of layers[3].

After identification of the first problem, it was rationalized the since the current circuit in the power supply for these magnets is floating there should be no problem as long as there was only one path of reduced resistance to ground. No concerted attempt was made to identify and fix the problem. Figure 1 shows the measured resistance to ground for the accelerator cell solenoids at four different times as follows:

1. After winding and assembly into the beam tube ("dry" condition 2005-2006)

2. After hydraulic flow tests (2005-2006)

3. After completion of the accelerator at DARHT

4. After operations one year later

It is evident from Figure 1 that the resistance to ground of the solenoid assembly shows signs of degradation over time and exposure to cooling water. Note thast the resistances measured in the "dry" state had been subjected to hydraulic testing during the original cell assembly at LBNL. There is an indication that the lower resistance to ground has somewhat stabilized based on the similar resistances measured on 11/7/2007 and 9/30/2008. The probable cause of the reduced shunt resistance is addressed below.

The reduced resistance in some of the cell solenoids is an indication of shorted turns. The reduction in the resistance corresponded to an integral number of layers[3] suggesting that the turn to turn shorts occurred at the end of the coil. Further investigation showed that the occurrance of the shorted turns was most often observed after the magnet had been on for an extended period of time. Tuzel, *et al.*[1] have shown the thermal expansion at the end of the coil introduces mechanical stresses that exceed the strength of the bond between the Formvar insulation and the copper conductor. Prior studies[4] to understand the failure modes of the solenoid coil also demonstrated that the bare conductor can be exposed when the coils is operated at nominal currents (12 A) without cooling. This study demonstrated that the binding strength of the Formvar to the epoxy is stronger that the binding strength of the Formvar to the copper wire. In addition to exposing the bare conductor, The destructive testing of the magnet caused azimuthal fractures in the epoxy

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extending to the full circumference. Althugh these fractures occurred at very elevated temperatures (180°C) after only 10-20 minutes, it is very likely that micro-fractures could occur after repeated cycling at lower temperature. The epoxy is known to be hygroscopic further degrading the ability of the coil the hold off voltage.

3 Common magnet testing specifications

The existing coil specification prescribes several acceptance tests[5]. In particular, Section 3.2.2 specifies that the leakage current at 1.5[kV DC] should be less than 2[μA]. This is equivalent to requiring a ground insulation resistance of greater than 750[MΩ]. In view of the analysis of historical trends in the currently installed magnets shown in section 2, the logic and feasibility of such a high specification was called into question and investigated.

A widely used text by J. Tanabe on the topic of magnet design and engineering was consulted initially[6]. Chapter 10 of the book covers magnet coil fabrication and includes typical testing and acceptance criteria. Tanabe writes, "The general requirements for the test is that the isolated coil should be capable of holding twice the operating voltage plus 1[kV]. At this test voltage, leakage current to ground should not exceed 2[μA]." DARHT-2 cell solenoids are typically energized with 12[A] of current resulting in less than 200[V] of potential. The present specification calling for a 1.5[kV] energization is thus consistent with the guidance provided by Tanabe.

Additional insight into common testing methods was obtained by talking with a practicing magnet engineer[7]. Chuck Swenson (LBNL) is presently the lead magnet engineer on the Advanced Light Source-Upgrade project at LBNL. In previous years, Chuck was a LANL employee and had also worked on aspects of the DARHT-II solenoid magnets. Several key points were made in this conversation:

1. His recollection was that it seemed that little to no dielectric design had been performed on the original coils designed by LBNL.

2. The testing specification found in Tanabe's book is a "tried and true" method for qualifying coils. It is useful to perform this test and verify insulator integrity.

3. It is often useful to define different hi-pot test methods: one for procurement phases of a project and one during operations. The main

point is that while a contractual relationship exists with a manufacturer, it is possible to hold them to a very high standard of quality. This is different than situations during operations where a breakdown event within a coil may sufficiently degrade it necessitating an adjustment in operations to work around the problem or even causing the facility to be taken offline for repair.

4. Finally, he recommended that if many coils were to be manufactured, that sending technical representatives to the fabrication site was often a wise move in order to ensure all specifications in the procedure are being followed.

In light of the historical and present practices in magnet design, it seems reasonable to take the following actions:

1. Retain the present testing specification of 1.5[kV DC] potential with leakage current less than 2[μA].

2. Future hi-pot testing of installed coils in DARHT should be evaluated with a different testing mechanism to ensure they are not damaged.

3. Re-evaluate the coil dielectric design to ensure it can be expected to meet the required hi-pot and shunt resistance.

4 Dielectric analysis

The updated magnet design is described in the presentation by Tuzel[1]. A key feature of the new design is to make use of the "heavy build" type of magnet wire as opposed to the original type[8]. The heavy build conductor has a finish dimension 0.008" larger than the previous conductor and is composed of polyamide-imide (PAI)[1]. Material properties of the PAI film are taken from ref. [9], extrapolated to DC frequencies. The potting epoxy used in the previous design is a 2-part epoxy produced by LORD and chosen for its relatively high thermal conductivity[2]. In the course of the study, a sealing coating was identified that is produced by Dow[10]. The electrical resistivity of these materials is summarized in table 1.

A simple model is used to estimate the shunt resistance and performance of a coil of conductor covered in various layers of dielectric. The simplified geometry is shown in fig. 2. In the cell solenoids, G-10 end-caps are used at

Table 1: Electrical resistivity, ρ, of dielectric materials used in the DARHT Axis-II cell solenoid magnets.

Function	Name	Elec. resistivity $[\Omega - \text{cm}]$	Information Source
Conductor insulation	Polyamide-imide (PAI)	5×10^{11}	ref. [9]
Structural epoxy	CoolTherm EP-301	1×10^{15}	ref. [2]
Conformal coating	DOWSIL 1-2577	5×10^{13}	ref. [10]
Coolant	Low Conductivity Water Supply	8×10^6	Typical facility value

the ends and eliminate this surface area from consideration. Interior layers are similarly covered by other layers and not considered. In this model, only the inner and outer surfaces of the right-circular cylinder are used as "exposed" surface area, A, defined as follows:

$$
\begin{aligned}
A &= 2\pi(R_i + R_o)h_{coil} \\
&= 2\pi 2 \frac{R_i + R_o}{2} h_{coil} \\
&= 4\pi R_{avg} h_{coil}
\end{aligned}
\tag{1}
$$

where R_i and R_o are the inner and outer radii respectively, R_{avg} being the average of the two radii, and the coil height is h_{coil}. From drawing 471773189, the average coil radius is approximately 5.73" or 14.55[cm]. From the same drawing, the coil height is 15.275" or 38.8[cm]. This yields a surface area from eqn. 1 of about 7100[cm²].

For a dielectric layer of thickness d_{min}, the total circuit resistance, R, through this layer is given by the following:

$$
R = \frac{\rho d_{min}}{A}
\tag{2}
$$

where ρ is the electrical resistivity. This assumes the coil is immersed in a conducting liquid such as a salt-water bath.[1]

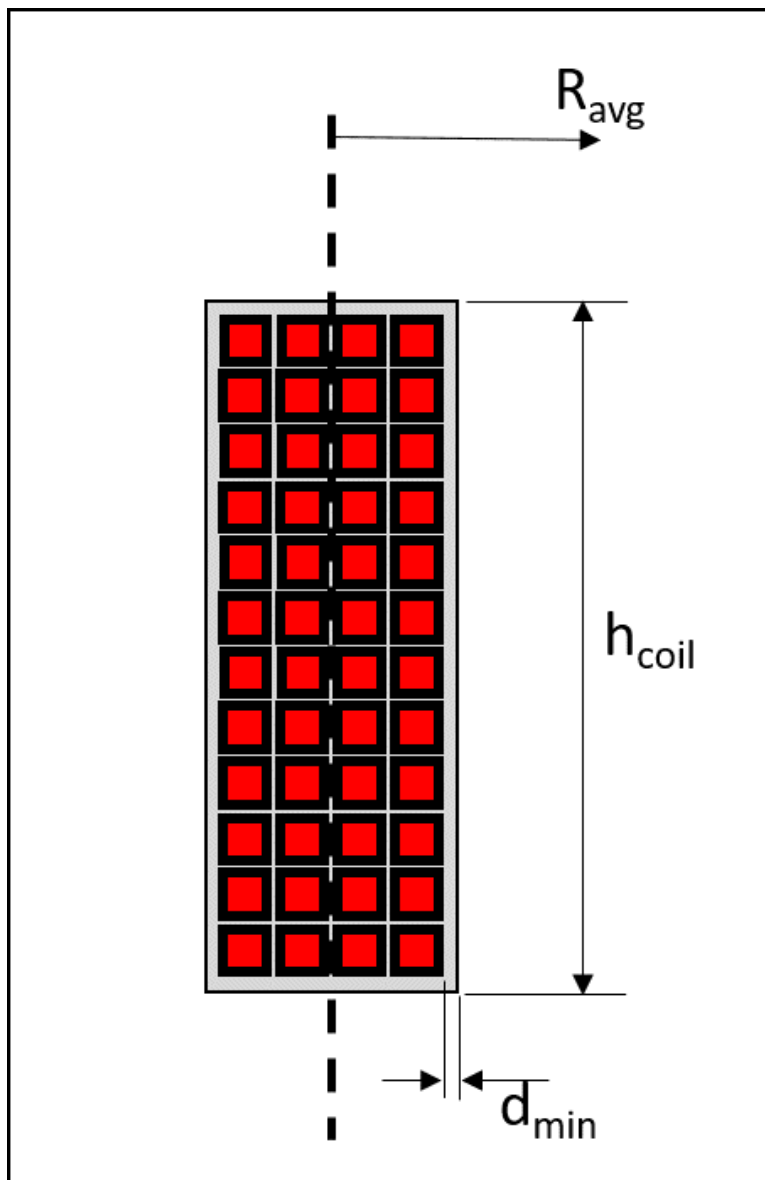[1] A slab geometry is used for this calculation owing to its simplicity and the fact that

Figure 2: Geometry of the coil used for analysis.

Table 2: Equivalent exposed surface area of copper in contact with the low conductivity cooling water to yield 1, 10, or 100[MΩ]. Fractions of a single turn of conductor required to result in this resistance. The coil-to-wall distance is assumed to be 0.25" with a water resistivity consistent with tbl. 1.

Resistance [MΩ]	Equivalent Area [cm^2]	Fraction of a Turn
1	5.1	27%
10	0.51	2.7%
100	0.051	0.27%

An interesting calculation is to consider what a minimum ground insulation resistance may be for these coils. If the epoxy were compromised or debonded, as suggested in the thermal/structural analysis by Tuzel[1], then only the PAI coating may be left. In this case, eqn. 2 indicates that a total coil resistance of 0.719[MΩ] would be a minimum coil resistance. This resistance is far below what is required by the specifications for the coil. Clearly, the epoxy thickness and integrity are critical to achieving a high quality coil.

Even in the case of an intact epoxy layer, the discussion in section 2 indicates bare copper may be in contact with the low-conductivity cooling water inside the beam tube. In this instance, eqn. 2 can be re-arranged to provide an equivalent exposed area through the water that would result in a given resistance. Further, given the azimuthal cracks observed during destructive testing, the fraction of the surface area of a single turn can be estimated from the known wire thickness and the average radius of the coil. Table 2 shows the results for achieving resistances of 1, 10, and 100[MΩ].

In the case of the LORD CoolTherm epoxy used in this design, if the full resistivity is achieved then the minimum thickness can be calculated to be 71[μm] or 0.0028" assuming a desired resistance to ground of 1[GΩ]. As the epoxy is applied by hand and may be subject to irregularities in composition (e.g. bubbles) or thickness, it seems prudent to assume less than full resistivity is achieved, say by a factor of 10. In this case, then, the thickness required would be $d_{min} = 710$[μm] or 0.028", which has the benefit of also being measurable with standard shop tools.

Examination of the coil fabrication procedure (ref. [5] rev. A) reveals

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the thickness of the dielectric layer is much less than the radius. For layer thicknesses of 0.010" on a coil of radius 5.73", the difference in resistance using the formula for coaxial conductors is less than 0.1% below the result assuming a slab geometry.

that no minimum thickness is guaranteed in the design. Step 19 reads:

> Apply Castall epoxy to outer diameter of the winding to build up a waterproof coating that isolates the winding from the cooling water. Ensure that the epoxy does not exceed the outer diameter as shown on the drawing. After applying epoxy coating, rotate the winding at about 8 RPM to form a uniform, smooth surface finish. Rotate until the epoxy has set. (p. 11)

As can be seen, no minimum thickness is specified or quantified. As a result, the minimum may be as small as *zero* leaving the coil with 0.719[MΩ] of resistance to ground.

Additional examination of the LORD CoolTherm epoxy has indicated that it is hygroscopic and will absorb 0.2% moisture[2] over the course of 10 days[2]. This is consistent with correspondence with Everson Tesla coil experts indicating that the immersion of these coils in cooling water (as is the intended use at DARHT) could compromise the epoxy and thereby the coil insulation. Everson Tesla experts suggested the use of a water-proof conformal coating layer composed of DOWSIL 1-2577[10].

The question arises whether the LORD CoolTherm epoxy could be eliminated from the design in favor of DOWSIL. Applying eqn. 2 to the resistivity shown in tbl. 1 yields a minimum thickness of 1.42[mm] or 0.056". The existing cooling channel width around the coil is 0.250" and should not be closed by more than 20%[1]. Making similar conservative assumptions for the conformal coating would result in a coating that completely closes the cooling channel gap and therefore fails to meet the design requirements of staying in the existing beam tube geometry.

5   Proposed magnet specification changes

As a result of the analysis in the preceding section, definite design changes will be used to improve the coil design. First, the overall design should use the CoolTherm epoxy as a structural and dielectric component to achieve the required resistance to ground. Second, the conformal coating should be used to seal the CoolTherm epoxy and prevent water infiltration to the underlying conductor insulation. Finally, steps should be added to guarantee

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[2]The manufacturer data sheet does not clarify whether this absorption amount is by weight or by volume.

the CoolTherm epoxy thickness and therefore achieve a minimum resistance to ground consistent with the coil specifications.

The updated coil specification (ref. [5] rev. B) now includes the application of the DOWSIL conformal coating as a final step. In addition, coil measurements before and after epoxy application are used to determine the achieved epoxy thickness during fabrication. The coil thickness measurements are to be recorded with the coil traveler so as to document the results. Finally, the electrical testing, coil-to-ground, will now include explicit recording of the leakage current in addition to the shunt resistance calculated during these tests to more closely follow the recommended specifications in refs. [6] and [7].

6   Conclusions

The DARHT-II cell solenoid magnets have recently been redesigned and the coil specifications re-evaluated. The recommended practices for coil acceptance testing are found to be consistent with the existing specifications. An analysis of the dielectric performance of the coil reveals that the epoxy potting layer is critical to achieving acceptable performance, however previous specifications did not provide a means to guarantee performance. Specific recommendations for improving the coil design are made which avoid redesign of the beam tube and allow for significant variability in the quality of the applied epoxy layers.

Acknowledgments

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